Operator focused automation of ROV operations*

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***Abstract*—Aiming to provide higher level of autonomy in operation of Remotely Operated Vehicles (ROVs) in subsea industries, this paper aims at identifying the tasks in ROV operations that would see the greatest benefits from automation efforts. Benefits in the sense of increased safety, reliability and reduced manning, leading to reductions in operational cost. To this end, this paper aims to present results of close cooperation among the ROV operator team and ROV automation team. This enables the ROV operators to be actively involved in the automation process and provide feedback such that the final solutions can be implemented and presented to the operators in a way that is most useful for them. The identified tasks are rated in terms of perceived workload and duration, and automation strategies developed in recent research are discussed for the most relevant tasks. The reported effort is tailored for IKM Subsea's Residential ROV, which is placed on the seabed for several months at a time, contrary to almost every ROV systems today, which are launched from a platform or ship and are submerged for short time periods (typically not more than 24-48 hours). The environment in which ROVs operate requires an extremely robust solution, because erroneous interventions could cause catastrophic consequences.**

I. Introduction

Despite tremendous efforts to realize autonomous ROV operations in the industry, the control and operation of work class Remotely Operated Vehicles (ROVs) for executing subsea repair and intervention operations still rely on expert ROV operators. The ROVs consists of numerous heterogeneous interacting components. Even with recent advancements in design and automation of ROVs, their efficiency and effectiveness highly depend on skill set of their operators. The complexity of the ROVs and presence of operators in the control loop defies the automation of ROV operations at the trajectory level in the classical sense. Hence, more rational approach is to automate the ROV operation at a higher task level. Each task generally consists of a sequence of minuscule trajectory control operations. Each ROV operator has his own way of executing the tasks, hence, the link between tasks and corresponding sequence of minuscule trajectory control operations is not unique. In despite of the extreme importance of human factors in operation of unmanned underwater vehicles, studies on effect of human factors associated with unmanned underwater vehicles is overlooked in the literature, see [1] as one of the few exceptions. Not paying enough attention to man-machine relationship in automation of ROV operation undermines the effectiveness of previous developments of autonomous functionalities in ROV operations.

It was this circle of ideas that motivates our current work to further study the effect of human factors in automation process of ROV operations. The current work is focused on Residential ROV (RROV) (Fig. 1) manufactured by IKM Technology AS [2], and operated by IKM Subsea AS [3]. While most of the work class ROV systems are launched from a platform or ship and are submerged for short period of time (typically not more than 24-48 hours), the RROV is placed on the seabed for several months at a time.

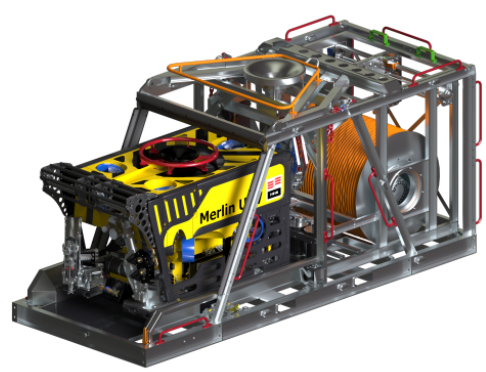

Fig. 1. The Residential ROV to be used as a test platform.

The operation of RROV is performed remotely, from Onshore Control Center (OCC), thanks to recent advancements in digitalization and remote technologies at IKMS [4]. The OCC operates just like the control rooms on offshore platforms and ships and is manned 24/7. The OCC and ROV operators, in combination with the RROV, plays an instrumental role on the current paper. The results of this paper are developed with continuous access to RROV and its operators in OCC. We strongly believe that for a successful ROV automation, we should consider the the interaction between the operator and automation system carefully and avoid a technology-centered automation approach. In this manner, we would be able to consider operators' behavioral, cognitive, and emotional responses to automation process [5]. This enables the ROV operators to be actively involved in the automation process such that the

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final solutions can be implemented and effectively exploited by them.

The current paper presents the first steps in an ongoing project, aiming to build higher level of autonomy in operation of ROVs, to improve safety, efficiency while reducing the cost of operating an ROV. The safety can be improved by shifting the operator's role from controlling the ROV directly, to monitoring the ROV's operation. Increasing efficiency is possible because the implemented functions will be tailored to fit the operations performed with the RROV, noting that most of these operations are typical ROV operations. The cost reduction will come as a result of less wear on components, which directly reduce equipment cost, but also costs associated with recovering the ROV system to perform maintenance and potentially reduced cost due to reduced manning.

To this end, the paper presents the various tasks that the RROV performs and specifies the functions of each operator involved in the operation. These tasks can be grouped into three main categories which are general for all ROVs:

- ROV navigation and station keeping.
- Manipulator and tooling control.
- Tether management.

The specific relevance of these general main tasks to the specific sub-routines performed with the RROV will be covered in detail. Finally, a safety analysis with and without these proposed solutions will be presented and the pros and cons will be discussed.

In [6] ROV assignments are categorized into contract work and call-out work. The call-out work is performed over relatively short time periods, while contract work are assignments where the ROV is integrated into a platform or ship. Contract work may be divided further based on what type of unit the ROV system is integrated with, namely stationary and mobile units. This distinction is important, as an ROV system integrated on a stationary unit allows for site specific automation solutions. [1] To better understand where increased automation will be most beneficial, it is useful to establish a measure of workload associated with each task that the operators perform. This workload and the average time spent on a task could be a useful tool when determining where automation efforts should be put.

The structure of the paper is as follows. In section II we present a concise survey on earlier efforts in ROV automation and expand on the topic of workload. In Section IV we present the method used for determining operator workload. In section V, typical ROV operations and the specific tasks are presented. Discussions, conclusions and suggestions for future research are summarized in Sections VI and VII.

II. Previous work

A. Autonomous intervention

In the recent years, there has been few initiatives trying to address the topic of autonomous underwater intervention; see [7]–[13] and references therein. In particular, the development review of intervention AUVs (I-AUV) presented in [8] is of interest. In [8], three experimental I-AUVs had been developed. They present three highly relevant tasks for subsea intervention:

- Subsea panel docking and fixed-base manipulation
  1) Acoustic navigation to vicinity of panel
  2) Vision based docking
  3) Valve connector plugging/unplugging and valve turning
- Free Floating Based Manipulation on a sub-sea Panel
  1) Acoustic navigation to vicinity of panel
  2) Simultanious station keeping and valve handling using learning by demonstration (LBD)
- Object recovery
  1) Optical survey
  2) Target detection and tracking
  3) Object grasping

The first two tasks are verified in a pool testing, while the third is verified in sea trials.

Another way of approaching the autonomous interventions were investigated in the SWIMMER project ([9], [10]), where a prototype AUV were designed and tested to be used to transport ROVs between docking stations. At the end of the project, an automatic docking had been performed. Although this system allows covering large areas using single ROV, the developed concept requires multiple docking stations with a tether management system (TMS).

Presented in [11] is a Hybrid ROV (HROV) that has power on board, but is tethered to the ship via a tether that contains fiber only. The prototype was tested in sea trials and were successfully able to operate to depths of more than 2000m.

The TRIDENT project ([12]) was a three year EU project that focused on developing I-AUV. The outcome of the project was an experimental AUV capable of autonomously finding and grasping an object.

[14] presents results from another EU-project called PANDORA. Among the results are an experimental I-AUV that can perform valve handling, which is accomplished through learning by demonstration. They also compare model-based and model-free vehicle control algorithms and perform underwater chain detection and following.

In the TRITON project, autonomous subsea panel detection and docking is performed, in addition to valve handling and so-called hot stab connections [15]. They note that a key element is a AUV-friendly intervention panel and that the main challenges were related to vision-based systems. To solve this, they suggest using light beacons instead of passive markers or colors for panel detection.

A recent project called DexROV [13] aims at making ROV operations cheaper and safer by

- Move control of ROVs to shore, from a safe distance.
- Overcome latency involved between onshore control centres and ROVs, through autonomous operations.

[1]The typical day rate of an ROV system ranges from $3000 to $50000, depending on whether one accounts for the cost of the ship.

- Develop advanced dexterous tools with the capacity to grip and manipulate in ways similar to a human hand.

The DexROV project has similar goals as our innitiative, but differs in the methodologies. We approache the shift towards automation by utilizing existing hardware and implementing academically developed software algorithms, accounting for practical considerations by involving operators in the development. This results in cost efficient development and rapid integration with the industry.

B. Human factors

In [16], Lumelsky found that a human operator has difficulties teleoperating a robot because it is difficult for operators to interpret the information presented to them. This issue becomes pronounced when the robot is operating in a complex environment with potential collisions.

To the best of our knowledge, there is very little research into the role and effect of human factors in underwater operations. while human factor considerations in unmanned aerial vehicle are reported in the literature, see [17], [18] and references therein, the role of ROV operators is mainly overlooked in underwater community.

The findings of over 150 papers covering issues and solutions related to perception and situation awareness for operators of tele-operated robots is presented in [19].

The human interfaces for ROV operations are assessed in [20]. A standard visual interface is compared to two augmented reality (AR) versions, one based on visual aids and one on audio aids. The interfaces are compered for a path following operation. It is concluded that both AR aids improve path following, both in high and low load environments. The findings that auditory aids can be well suited for directional navigational tasks are supported by e.g. [21]–[23]. The issue of path following is something that should be handled autonomously. However, for tasks that do not have mature automation solutions and where the operator uses inputs that can be interpreted as a directional signal seem promising.

The application of haptic feedback devices for use in ROV operations is investigated in [24], where the main aim is to provide the user with a sensation of forces and moments acting on the ROV. The device developed use propellers to provide orientation force feedback and is very much in the development stage. However, using some kind of haptic feedback device could be very useful if it could represent the force on the manipulator, e.g. through force sensors. This is because the manipulators are the equipment that experience the most force, relative to their strength, as operators have difficulties assessing how hard they are hitting objects.

In [25], visual perception is claimed to be the most important factor for improving effectiveness of ROVs. They suggest using CAD models to provide ROV operators with a 3D model covering the vehicle and surrounding environment with real time rendering. These findings are corroborated by [1].

From the literature, it seems evident that the focus has been put on increasing the situational awareness of the operator by optimizing how information is presented to the operator. However, this approach can only improve operations to a certain extent. In order to reduce manning (thus reducing cost) and improve reliability and safety, autonomous functions must ultimately be introduced. This claim is further strengthened when the operators are moved onshore, as this increases delay and periodical loss of communication.

III. Operator workload

Despite being a well known topic, the notion of workload does not have an accepted definition or measure [26]. Measures of workload are divided into physiological, subjective and performance-based measures. The most important aspect of a measure is its sensitivity, that is, its ability to increase and decrease with the workload.

Whether subjective measures are as sensitive (or more sensitive) as physiological and performance-based measures can be argued (see [27] and the references therein). However, it does seem that subjective measures are regarded as more convenient and less time-consuming. Subjective measures are further divided into unidimensional and multidimensional measures.

Comparison of the four most researched subjective workload measures are presented in what follows, for more details the reader is referred to [28].

A. Modified Cooper-Harper

The Modified Cooper-Harper (MCH) scale is a unidimensional scale that ranks the workload from 1 to 10 [29]. The measure uses decision trees to aid the user in choosing a rating.

B. Overall Workload

The Overall Workload (OW) scale is another unidimensional measure that simply rates the perceived workload from 0 to 100, corresponding to very low and very high workload, respectively.

C. NASA Task Load Index

Hart and Staveland [30] developed the well-known multidimensional NASA-TLX (Task Load Index). The index rates performance, effort, frustration, and mental, physical and temporal demand on a 21-point scale.

D. Subjective Workload Assessment Technique

Subjective Workload Assessment Technique (SWAT) [31] is another multidimensional technique for determining workload. SWAT employs three dimensions; time load, mental effort load and psychological stress load. Each of the loads are ranked from level 1 to 3 with descriptions for each level to aid the user in making a decision.

There seems to be a general consensus that workload is multidimensional. However, [32] argues that unidimensional measures are better suited when one is interested in the overall workload. Also, [28] compares the four abovementioned methods and concludes that NASA-TLX and OW are superior in terms of sensitivity. These were also the methods preferred by operators and OW required significantly shorter time to complete than the other methods.

The impact of Level of Automation (LOA) on system performance during a multitask designed to mimic the tasks performed in piloting, air traffic control and etc, are investigated in [33]. Experiments with subjects showed that performance increases when the task implementation is automated, but only if the automation does not fail. In the case that automation fails, the operator performance is worse than if the operator performed the task by herself. In addition to rating the performance of the human/system, the subjects also performed a NASA-TLX questionnaire post simulation. The results showed that the total subjective workload decreased significantly with increasing LOA and that all of the subcomponents of the index were positively correlated with the total score. Thus, this study creates a strong rationale for automating implementation of tasks.

An interesting observation is reported in [34]. The performance increased with increased LOA and that subjective workload (NASA-TLX) decreased with increased LOA. On the other hand, there were performance degradation associated with return-to-manual control compared to pure manual control and this degradation increased with LOA. They also found that the experience that the operator has in interacting with an autonomous system is important for the overall performance. From the reported results and conclusion, it seems as though the greatest benefits are obtained when increasing LOA in the lower levels.

Another interesting observation is presented in [35]. The probability of an operator using automatic control functions followed an S-curve with increasing trust in the system and self-confidence, highlighting the importance of operator training. Not only in using the system, but also training in how the system works.

Low operator workload has been associated with degraded performance (see [36] and references therein). However, [37] found that this might be as a result of motivation and that increasing intrinsic motivation through increased competence and relatedness can eliminate these effects.

IV. Method

As one of the early steps in our project, a list of the common operations performed with the RROV is prepared by one of the pilots. The pilot has over 30 years of experience from ROV operations, both offshore and onshore. The list includes a breakdown of the subtasks performed by the pilot and the co-pilot. Furthermore, a typical time duration required for execution of each task is specified.

Based on this list, several pilots working with the RROV system were asked to perform a SWAT assessment for each subtask. Usually, this is meant to be performed right after a task have been completed. However, to reduce the invasiveness of the questionnaire and because the subjects have been working with these types of operations for several years, the questionnaire is performed when the pilots have free time. It should be noted that this method was chosen because we believed it to be the least invasive and time consuming method, while still providing a multidimensional rating.

Let x_T, x_M and x_P be the SWAT score given to the temporal, mental and psychological stress components, respectively. Then the total workload is

$$S = x_T x_M x_P. \quad (1)$$

Taking time into account, the accumulated total workload is

$$S_{acc} = T_{task}(x_T x_M x_P) \quad (2)$$

where T_{task} is the average time spent on a task.

V. Results

In the following, the most common types of operations performed with the RROV is presented.

Valve handling

Consists of flying the ROV from the cage to the requested manifold. The main focus of the pilot is to maneuver or fly the ROV and operating the grabber. The main task of the co-pilot is to open or close the valve, using the manipulator. For some valves it is required to use a torque tool to apply the correct torque to the valve. An example of a valve handling task is shown in Table I.

Choke handling

This operation is similar to the valve handling operation. A choke is similar to a valve, but the term choke is specifically used for valves that perform flow and pressure control [38].

General visual inspection

Consists of flying the ROV from the cage to the requested subsea structures for visual inspection.

Assist WROV in various operations

In addition to the RROV, there is a WROV that carries out tasks that are not as common, that involve heavy lifting and other high risk activities with regards to equipment. Structurally, the RROV and WROV are equal but since the RROV stays submerged for extensive periods, these activities are avoided to minimize the probability of having to recover the RROV.

Bullseye inspection

The pilot flies the ROV to the requested structure and inspects the bullseye, which shows the inclination of the structure.

Based on the identified operations and tasks, 8 ROV pilots have rated each task, using the SWAT score.

The subtasks that the pilot and co-pilot perform can be grouped into the following

- Pre-flight check.
- ROV station keeping.
- ROV maneuvering or flying the ROV.
- Simultaneous ROV and grabber or tooling operation.
- Simultaneous ROV and skid operation.

Co-pilot

- Pre-flight check.

Phase	Pilot	Co-pilot	Time
Preparation	Pre-flight check	Start datalogging	2 min
Fly to target	Fly ROV	-	2 min
Open manifold hatch with grabber	Fly ROV and operate grabber	-	2 min
Position ROV with valve in manipulator reach	Fly ROV	-	1 min
Get tool from skid	Station keeping and operate skid	Operate manipulator	2 min
Place tool in valve bucket	Station keeping	Operate manipulator	2 min
Open/close valve	Station keeping	Operate manipulator and log valve state	1 min
Close manifold hatch	Fly ROV and operate grabber	-	2 min
Return to cage	Fly ROV	-	2 min
Park ROV in cage	Land ROV	-	1 min

TABLE I
EXAMPLE OF OPERATION.

	Temporal			Mental			Stress			Total		
Task	Onshore	Offshore	All	Onshore	Offshore	All	Onshore	Offshore	All	Onshore	Offshore	All
Pilot pre-flight check	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
ROV station keeping	1.00	1.11	1.04	1.03	1.44	1.19	1.00	1.44	1.17	1.03	2.32	1.44
ROV maneuvering	1.00	1.00	1.00	1.03	1.09	1.05	1.00	1.04	1.02	1.03	1.13	1.07
ROV and grabber	1.00	1.00	1.00	1.03	1.00	1.02	1.00	1.00	1.00	1.03	1.00	1.02
ROV and skid	1.00	1.17	1.06	1.00	1.33	1.13	1.00	1.33	1.13	1.00	2.07	1.34
Co-pilot pre-flight check	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Manipulator operation	1.00	1.21	1.08	1.04	1.85	1.34	1.00	1.88	1.33	1.04	4.21	1.92

TABLE II
SWAT SCORES FOR ONSHORE AND OFFSHORE PILOTS AND THE AVERAGE SCORE FOR ALL PILOTS.

- Co-pilot. Referring to various tasks such as TMS operation and navigation. This task is excluded from the analysis.
- Manipulator operation.

The average monthly time spent on each of these tasks are shown in Fig. 2. The duration of the various tasks can vary quite a lot and is reflected in the dark and light regions in the Figure. Fig. 3 shows S_{acc} as defined in (2). Operating the manipulator is an obvious workload driver. According to the pilots, the manipulator used on the RROV can be unpredictable and jerky or chattery when interacting with subsea structures. This makes the ROV pilots uncertain, which is also reflected when looking at the average SWAT score for each task in Table II. In general, the workload is quite low. This makes it difficult to compare the tasks and is a drawback of the SWAT method. In general, the subjective workload of the offshore pilots is higher than that of the onshore pilots. However, there were only three offshore pilots among respondees.

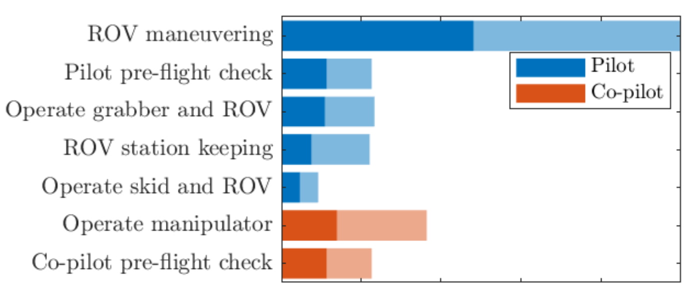

Fig. 2. Average monthly time spent on each task. The dark and light areas represent the minimum and maximum time, respectively

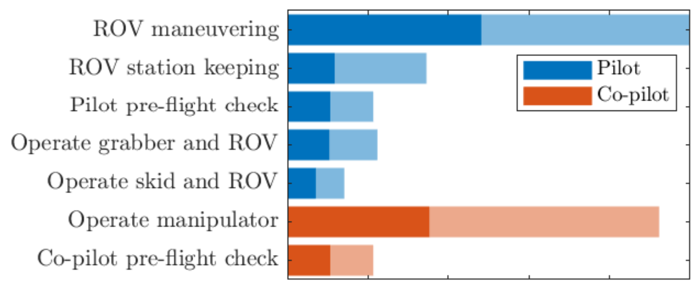

Fig. 3. Average monthly workload for each task. The dark and light areas represent the minimum and maximum workload, respectively

VI. DISCUSSION

A. Manipulator operation

Using the manipulator is by far the task associated with the highest subjective workload. It is also being used quite often, so improving the use of the manipulator could certainly improve operations. The control algorithm of the manipulator should be improved to eliminate jerky or unpredictable behavior. Further, the manipulator is rate controlled and the operators use a pendant arm to control each joint of the manipulator. The pendant arm is a miniature version of the manipulator and the pilots need to use both hands when controlling it. I.e. it is impossible to do anything else while controlling the manipulator. By implementing position control of the tool center point (TCP), the manipulator control can be performed using only one hand. This enables the pilot to control the manipulator and ROV simultaneously and could lead to significant operational improvements because the operator controlling the manipulator does not need to communicate with the pilot for the ROV to move where he wants. There are several ways to implement TCP control and since the control is performed in small increments, i.e. continuous inputs from a joystick, one does not require path planning. It is worth to mention that, the way the control is implemented is somehow non-trivial, as it is important that it is intuitive and natural to the pilots. Natural in the sense that the various joint moves somewhat in the way that they would if the operator had control over each joint, as with the pendant arm. Any update in this line should be checked with operators to confirm that the final results feels natural to them.

Taking the automation process of the manipulator operation one step further, the TCP control can be combined with the station keeping. For example, by attempting to position the ROV so that the joints of the manipulator approach some desired positions, giving the manipulator maximum operating range, by incorporating the thrusters directly into the TCP control or by simply accounting for the coupling effects. Some of these methods have been proposed in earlier articles such as [39] and [40]), but few have been tested in industrial applications.

B. ROV maneuvering

As seen in Fig. 2, much of the operational time is spent on maneuvering or flying the ROV. The RROV is operated in a stable environment with fixed structures and few environmental forces and unknowns. In this aspect, autonomous maneuvering from one place to another appears to be almost trivial with today's advancements within SLAM and similar approaches. However, light and other electromagnetic waves do not travel far in water, which introduces some additional challenges. Still, the combination of sonar, cameras and an environment that seldom changes should be achievable. Offline and experimental validation of a sonar based SLAM is presented in [41].

To account for unknowns such as other ROVs, an obstacle detection system is required. RROV is already equipped with an obstacle detection algorithm developed and tested [42]. When the ROV knows where it is, maneuvering can be achieved through the station keeping and guidance system implemented on the RROV [43].

C. Tether Management

The presented results mention little about the Tether Management System (TMS). The TMS connects the ROV to the ship or platform. The TMS has a drum with tether and the pilots controls the amount of tether that is on the drum. The amount of tether out is kept to a minimum to avoid the tether snagging in subsea structures but must be long enough so that the ROV can move freely. The pilots control the amount of tether that is out by monitoring the drum using cameras. Controlling the TMS is one of various continuous tasks not mentioned in the Section V. Currently, there are little published work on autonomous tether management systems for ROVs. This aspect of the ROV operation may have been overlooked but is critical for a smooth and efficient ROV operation. Since the feedback to the pilots are by cameras, an interesting approach to automating the TMS operation is to train a machine learning model on camera images using convolutional neural networks in which the label of the images would be the input from the pilots.

VII. Conclusion

Aiming to provide higher level of autonomy in operation of Remotely Operated Vehicles in subsea industries, this paper has identified a series of high level tasks in ROV operations that could be executed autonomously. Two tasks have been identified to be of great importance with regards to relieving the operators of work and enabling single-pilot control, namely manipulator operation and ROV maneuvering. As for manipulator operation, the main benefit is achieved by enabling the pilot to control the manipulator with one hand. This lets the pilot to control the ROV and manipulator simultaneously, allowing for greater accuracy and efficiency. Secondly, control of the TCP can be combined with ROV station keeping allowing the pilot to control the manipulator TCP with one hand while the other controls the grabber, skid or other tools.

In automating the ROV maneuvering, much work has already been performed, global and local localization of the ROV is a missing component. With the combination of a mostly static environment, sonar and cameras, this could be achieved well known methods within SLAM.

***Index Terms*—Unmanned underwater vehicles, Remotely Operated Vehicle, Autonomous vehicles, Teleoperators, Robot control**

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